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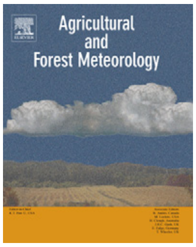

Agricultural and Forest Meteorology

Comparison between open-site and below-canopy climatic conditions in Switzerland during the exceptionally hot summer of 2003

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ABSTRACT

We compared open-site and below-canopy climatic conditions from 14 different sites in Switzerland based on LWF (Long-term Forest Ecosystem Research) data. The 14 sites represent different locations, orientations and elevations, from the Jura Mountains to the southern side of the Alps, composed of deciduous, coniferous and mixed forests. Meteorological measurements were carried out under the canopy at the observation plots, and in open areas outside the forest plots. We analysed air temperature during summer 2003, in connection with the exceptionally high temperatures measured during that summer and during the 11-day August heat wave. We compared minimum and maximum daily air temperature differences between open-site and below-canopy conditions.

We found clear differences between below-canopy and open-site temperatures. Maximum temperatures were on average up to 5.2 K cooler under the canopy during the 11-day heat wave episode in August 2003. There was a significant correlation between the absolute value of temperature and the difference between open-site and below-canopy temperature: the warmer the temperature, the stronger the impact of the forest. For maximum temperature, the difference was higher in deciduous and mixed forests, especially those with beech as the dominant tree species, compared to conifer forests. For minimum temperature, in contrast, the discrepancy was higher in conifer forests but, as for maximum temperature, it was also higher during warmer episodes. South-oriented slopes showed greater differences for maximum temperature whereas north-oriented slopes showed greater differences for minimum temperatures.

Our results quantify the role of forests in providing a cool shelter during heat waves. The results are of particular value to urban areas, where forested parks could provide an important source of relief during heat waves. Within a central European context, the most efficient ecosystems for this purpose appear to be beech, beech–silver fir and Oak–Silver Fir forests. The opposite effect was seen in mugo pine and Scots pine forests, with warmer temperatures under the canopy compared to open-site.

1. Introduction

It is now well known that forest microclimates are influenced by the canopy and by the presence of tree trunks (Chen et al., 1993; Geiger et al., 2003; Grimmond et al., 2000; Lee, 1978; Oke, 2000). Branches, leaves and needles reflect and absorb part of the direct solar radiation during the day, allowing less energy to reach the ground below the canopy. The presence of

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abundant biomass causes part of the radiation to be turned into metabolic energy instead of higher air temperature. During the night, infrared heat released from both the ground and plants is partly held back by the canopy. This explains why forested areas usually cool down less during the night and limit daytime air warming.

Another feature of the forest microclimate is that there is less mixing of air due to turbulence. Most of the time, the air is cooler as the canopy's impact exceeds any effect caused by the lack of turbulence (Flemming, 1995). In contrast, the temperature can also be higher if the cooling effect due to wind is less than the warming effect of radiation under a thinner canopy. For instance, measurements in Mediterranean areas of arid, xerophilic vegetation have indicated that average monthly temperatures can be higher below-canopy than in open ground situations (Pavari, 1959).

The type of woodland formation (age, botanical association, silvicultural management system, etc.) determines the canopy's structure and form. Radiation penetrates a low-density woodland canopy more easily than the normally dense canopy of a pole-stage forest. However, once through the upper canopy, the amount of radiation reaching the ground is determined by the density of the vegetation layers between the canopy and the ground. In coniferous woodland, the energy reaching the ground can show substantial spatial variations, whereas in temperate broadleaved woodland there is generally less spatial heterogeneity (Flemming, 1995). The patterns observed in cool climate forests may also differ substantially from those observed in hot, dry climates (Grimmond et al., 2000; Lee, 1978).

Although many studies of forest microclimate have been carried out (e.g. Carlson and Groot, 1997; Friedland et al., 2003; Porte et al., 2004; Potter et al., 2001), the forest's impact on temperature during heat waves, the frequency of which will probably increase with climate change (IPCC, 2007), is still poorly documented. The objective of the present study is to compare below-canopy and open-site temperatures in order to determine the forest's impact, and to explore those differences when outside temperatures are particularly high. We chose the exceptional climatic conditions of summer 2003 to examine these effects. In Switzerland, the mean temperatures for summer (JJA) were 4–5.5 °C above the average temperatures measured since 1864 (Schaer and Jendritzky, 2004; Schaer et al., 2004). Throughout much of western and southern Europe, both maximum and minimum temperatures during that period were 3 °C to more than 5 °C above seasonal baseline (Rebetez, 2004a; Rebetez et al., 2006). In this context, the first two weeks of August were even more exceptional, with 11 consecutive exceptionally hot days above norms, coinciding with an increase in human mortality rates, especially in larger cities (Conti et al., 2007; Ferron et al., 2006; Filleul et al., 2006; Fouillet et al., 2007; Grize et al., 2005; Vandentorren et al., 2004).

2. Data and methods

LWF (Long-term Forest Ecosystem Research) meteorological data have been collected since 1997 in 17 plots in Switzerland, 14 of which were used for the present research (Fig. 1). They represent different locations, orientations and elevations, from the Jura Mountains to the southern side of the Alps, composed of deciduous, coniferous and mixed forests. They are located in all six biogeographic zones of Switzerland: Jura, Plateau, Pre-Alps and northern side of the Alps, inner and western Alps (Valais), inner and eastern Alps (Grisons) and the southern Alps (Tessin). Each of these regions is distinguished by its flora and fauna, determined by climate, environment

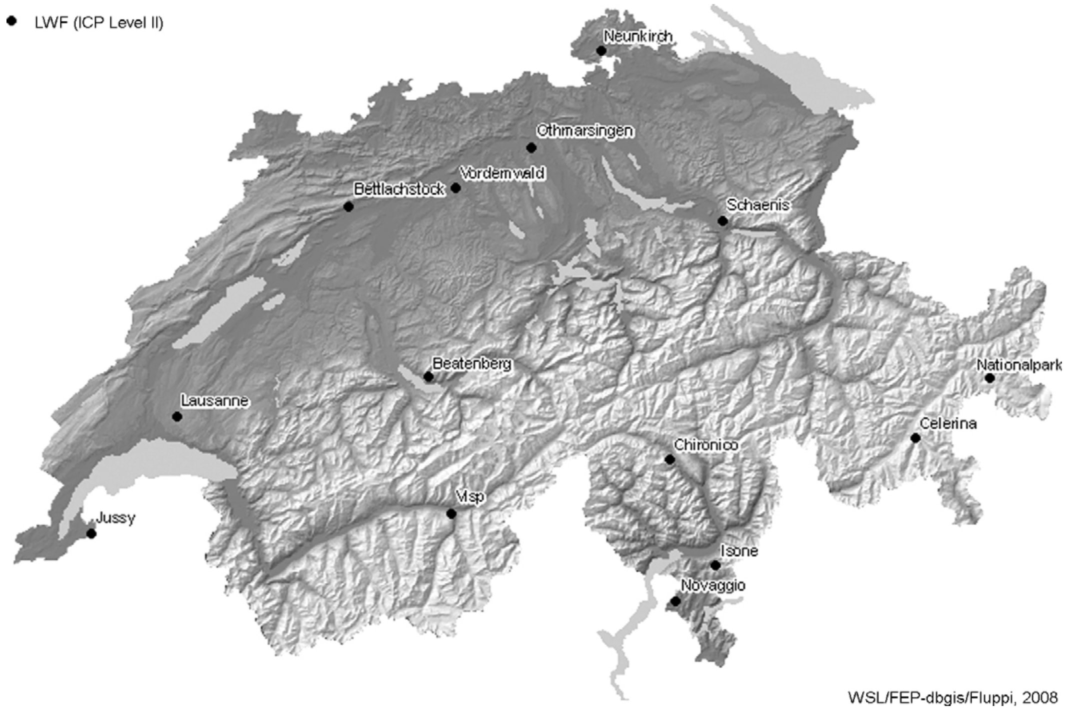

Fig. 1 – LWF plots distribution.

(relief, exposition, altitude, ground, soil, etc.), evolution and human presence. The vegetation levels are mainly determined by altitude, usually classified as Hill-, Mountain- and Subalpine zones (Rebetez et al., 2004c).

Five plots are located in the Hill zone (450–700 m a.s.l.): *Jussy* (500 m a.s.l.), *Othmarsingen* (500 m a.s.l.) and *Vordemwald* (480 m a.s.l.) on the Swiss Plateau, *Neunkirch* (600 m a.s.l.), on the south-facing flanks of the Jura Mountains and *Visp* (650 m a.s.l.) in the south-central alpine Rhone Valley, a very dry location with important thermal contrasts. Six plots are located in the Mountain zone (700–1400 m a.s.l): *Schänis* (700 m a.s.l.) on the northeastern side of the Alps, *Lausanne* (800 m a.s.l.) on the southwestern and *Bettlachstock* (1100 m a.s.l.) on the southeastern side of the Jura mountains, *Novaggio* (900 m a.s.l.), *Isone* (1200 m a.s.l.) and *Chironico* (1350 m a.s.l.) in the southern Alps (Ticino). Three plots are located in the Subalpine zone: *Beatenberg* (1500 a.s.l.) on the northern side of the Alps, *Celerina* (1850 m a.s.l.) and *Nationalpark* (1900 m a.s.l.) in the inner eastern Alps.

Meteorological measurements were carried out under the canopy at the observation plots, and in an open field outside the plots. For the latter, the meteorological station was always located less than 2 km from the plot, in a region of similar topography (altitude, slope orientation, distance from the bottom of a valley, etc.). The measurements for each site, available in real time, were stored and treated in a database. The thermometers were placed 2 m above ground, inside a circular metal shelter. Measurements were recorded every 10 min. The reliability of these thermometers has been checked by comparison with data from MeteoSwiss stations (Logeay and Rebetez, 1999) with excellent results. In order to measure the forest effect on temperature during particularly hot periods, for the 14 sites described above, we analysed the data from three time periods in 2003: April–October, JJA and the hottest 11-day period 3–13 August. For April to October 2003, nearly 100% of the data were available for most sites, approx. 90% for Bettlachstock, Isone and Lausanne, 86% for Schänis and Neunkirch and 78% for Othmarsingen. For the 3–13 August period, insufficient data (53%) were available for Isone. We computed the correlation coefficient r and applied Wilcoxon's tests (Bauer, 1972) and ANOVA tests to check the significance level of the temperature discrepancies between open-field and below-canopy values.

To compare the impact on temperatures of solar radiation reaching the ground, we analysed the LWF open-field and below-canopy PAR (Photosynthetically Active Radiation) measurements, recorded every 10 min on all plots except Novaggio. We computed the correlation coefficient r between daily maximum and mean temperature on one hand and daily maximum and mean PAR values on the other. For a comparison of the canopy closure degree between the different plots, we used LAI (Leaf area index) values (Schleppi et al., 2007), (Table 2) measured near the below-canopy meteorological station in 2004 (except at Beatenberg, measured in 2001).

3. Results

Maximum temperature values were lower below-canopy than in the open-field for 13 out of 14 sites for April to October and 12 out of 14 for JJA and the hottest 11-day period (Table 1): at the two Pine sites, maximum temperatures were mostly higher below-canopy than in the open-field. The strongest difference between below-canopy and open-field values for the three periods were measured at Othmarsingen and Schänis, two sites for which missing data were relatively important (~30% for the summer time scale). However, Bettlachstock and Vordemwald had similar results with almost complete data for the whole period. A typical illustration of the diversity present in the daily differences between below canopy and open field temperatures is shown for Beatenberg and Neunkirch (Fig. 2): the temperature difference did not vary at Beatenberg as much as at Neunkirch, where it was clearly higher from July to September. The difference in maximum temperature between below-canopy and open-field data increased during JJA compared to April–October for 9 sites out of 14 (Table 1). It increased even more during the 11-day period for 8 sites out of 14. This is confirmed by the Wilcoxon's test: the discrepancies between open-field and below-canopy maximum temperature were highly significant ($p < 0.001$) for 9 sites out of 14 from April to October, 11 sites for JJA, 9 for the 11-day period. The Pine sites were never significant and even inversely significant (Visp, 11-day period).

Minimum temperatures were higher below canopy compared to the open field data for 10 sites out of 14 from April to October (Table 1). Results were significant for 7 sites. Visp and Celerina had the most significant differences. For the 7 significant sites, the difference between below-canopy and open-site minimum temperatures were more pronounced during JJA and even more so during the 11-day period compared to April–October, and the significance level was higher. Four sites had lower minimum temperatures below

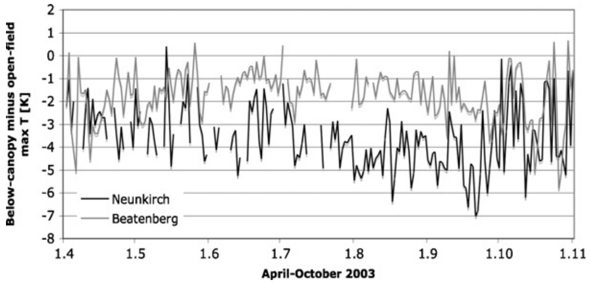

Fig. 2 – Difference in maximum temperature [K] between below-canopy and open-site at Neunkirch and at Beatenberg.

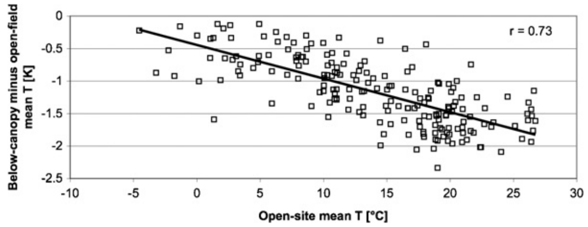

Fig. 3 – Correlation between below-canopy vs. open-field difference in mean *T* and open-field mean *T* at Bettlachstock.

Table 1 – Difference between below-canopy and open-field max *T* and min *T* [K] during three time periods in 2003 and *r* correlations between differences [K] and the absolute temperature for max and mean *T*.

Site name		Forest type	Difference between below-canopy and open-field [K]						*r* correlations between April and October difference and *T*	
			T max April–October	*T* max JJA	*T* max 3–13 August	*T* min April–October	*T* min JJA	*T* min 3–13 August	*r* max *T*	*r* mean *T*
Othmarsingen	S	Beech	-3.93^{**}	-4.80^{**}	-5.42^{**}	0.35	0.37	0.80^{*}	0.73^{**}	0.58^{**}
Schänis	W	Beech, Silver Fir	-3.75^{**}	-4.72^{**}	-4.93^{**}	0.28	0.33	0.87^{*}	0.60^{**}	0.53^{**}
Bettlachstock	S	Beech, Silver Fir	-3.37^{**}	-4.00^{**}	-4.44^{**}	−0.12	−0.14	−0.16	0.66^{**}	0.73^{**}
Neunkirch	N	Beech	-3.60^{**}	-3.81^{**}	-4.58^{**}	1.45^{*}	1.69^{**}	3.72^{**}	0.45^{**}	0.07
Vordemwald	NW	Oak, Silver Fir	-3.16^{**}	-3.53^{**}	-3.74^{**}	1.29^{*}	1.39^{**}	1.55^{*}	0.58^{**}	0.70^{**}
Isone	NE	Beech	-2.56^{**}	-3.16^{**}		−0.08	−0.16		0.73^{**}	0.79^{**}
Lausanne	NE	Beech, Silver Fir	-2.46^{**}	-2.99^{**}	-2.85^{**}	−0.65	-0.72^{*}	−0.23	0.50^{**}	0.67^{**}
Jussy		Oak	-2.12^{*}	-2.70^{**}	-2.29^{**}	1.22^{*}	1.37^{**}	1.92^{**}	0.60^{**}	0.70^{**}
Chironico	N	Spruce	-2.47^{**}	-2.47^{**}	-2.20^{**}	1.48^{*}	1.70^{**}	2.10^{**}	0.29^{*}	0.08
Celerina	NE	Larch, Arolla Pine	-2.57^{**}	-2.26^{**}	-2.73^{**}	3.00^{**}	3.48^{**}	5.28^{**}	0.09	0.08
Novaggio	S	Oak	-1.34^{*}	-2.01^{**}	−1.23	0.42	0.25	0.06	0.49^{**}	0.69^{**}
Beatenberg	SW	Spruce	-1.70^{*}	-1.29^{*}	-1.30^{*}	0.35	0.33	1.29^{*}	0.09	0.12
Nationalpark	S	Mugo Pine	+0.22	+0.46	+0.71	−0.16	−0.21	−0.31	-0.43^{**}	-0.22^{*}
Visp	N	Scots Pine	−0.36	+0.54	$+1.15^{*}$	1.67^{**}	2.05^{**}	4.05^{**}	-0.42^{**}	-0.63^{**}

[*] $p < 0.05$.
[**] $p < 0.01$.

Table 2 – Below-canopy part of open-site photosynthetically active radiation (PAR) [%] and r correlations between below-canopy and open-field April–October temperature difference and below-canopy and open-field PAR difference with maximum and daily mean.

Site name	Aspect	Forest type	LAI	Below-canopy part of open-site PAR [%]						r (below-canopy and open-field April–October T difference/PAR difference)	
				April–October		JJA		April			
				Max	Mean	Max	Mean	Max	Mean	Max	Mean
Isone	S	Silver Fir beech	5.8	14	7	7	2	62	39	0.75^{**}	0.87^{**}
Schänis	W	Silver Fir beech	5.5	15	7	11	3	48	31	0.64^{**}	0.74^{**}
Jussy		Oak	5.8	14	4	12	2	29	17	0.64^{**}	0.72^{**}
Bettlachstock	S	Beech	6.5	17	5	12	3	46	19	0.74^{**}	0.86^{**}
Lausanne	NE	Silver Fir beech	6.9	18	4	14	1	51	19	0.56^{**}	0.65^{**}
Vordemwald	NW	Silver Fir, Oak	5.1	14	3	16	3	20	4	0.57^{**}	0.69^{**}
Othmarsingen	S	Beech	4.6	19	7	17	4	47	34	0.68^{**}	0.74^{**}
Beatenberg	SW	Spruce	1.9	19	6	19	6	24	7	0.48^{**}	0.39^{**}
Chironico	N	Spruce	3.7	29	7	32	7	47	9	0.46^{**}	0.29^{*}
Neunkirch	N	Beech	5.2	22	6	33	5	21	17	0.44^{**}	0.22^{*}
Viège	N	Scots Pine	2.3	72	44	84	51	75	39	0.02	-0.22^{*}
Nationalpark	S	Mugo Pine	1.3	80	46	85	48	78	43	0.25^{*}	-0.19^{*}
Celerina	NE	Larch, Arolla Pine	1.2	94	42	100	41	96	52	0.27^{*}	−0.22

* $p < 0.05$.
** $p < 0.01$.

canopy compared to the open field for all three-time scales, but these differences were not significant.

The correlation between open-field absolute temperatures on the one hand and the discrepancies between open-field and below-canopy temperatures (Table 1) on the other was significant in mixed broad-leaved and broad-leaved forests for both maximum and daily mean temperatures, except at Neunkirch where the correlation was significant only for maximum temperature. A typical example of this correlation is shown for Bettlachstock (Fig. 3). There was no correlation for some of the conifer-dominated sites, and even a negative correlation for the two Pine sites. Minimum temperatures did not show any significant correlation between the absolute temperature values and the differences between open-field and below-canopy values.

At the broad-leaved forest sites, the strongest discrepancy between open-field and below-canopy maximum temperatures was observed during the hottest period. For the stations dominated by coniferous trees, the strongest discrepancies were observed in spring and autumn.

Below-canopy PAR relative values compared to open-field PAR values were higher for maxima than for daily mean values for all stations (Table 2). The highest relative values for below-canopy PAR were at the two Pine sites and at the Larch/Pine site, both for the maxima and the mean, and for April–October and summer. Low relative values in summer for the maxima and the mean were seen at most mixed broad-leaved and broad-leaved forests. At Chironico and Neunkirch, the maxima were high but daily mean values were low.

There was an important difference between April–October and summer at Isone (Fig. 4a), and at most mixed broad-leaved and broad-leaved forests (Table 2). The relative part of PAR radiation below-canopy was usually lower in summer than from April to October. It was more so for the maxima than for mean values, except at Jussy and Othmarsingen. At Visp (Fig. 4c) and Nationalpark, both Pine sites, it was the other way around for both the mean and the maxima. At Neunkirch and Celerina, PAR values were clearly higher in summer for the maxima but not for the mean. There was no difference at Chironico (Fig. 4b) or Vordemwald for mean values but relative PAR was higher in summer for the maxima, and there was no difference for either the mean or the maxima at Beatenberg.

The difference between relative PAR values in April compared to summer was highest in the deciduous forest sites. Isone is a good example (Fig. 4a and Table 2). It was not so in conifer forests or at Vordemwald, a mixed forest with *Abies alba* as the dominant species.

The correlation (*r*) between relative maximum temperature and relative maximum PAR was significant for all stations except Beatenberg (Table 2). For mean values, the three Pine or partly Pine sites had significant negative correlations, whereas all other stations had positive correlations, some of which were highly significant. After budburst, the deciduous and mixed stands had the highest degree of LAI canopy closure whereas the conifer stands had a lower degree of canopy closure.

The results of the ANOVA tests confirm the differences in the effectiveness of both forest types (spruce/beech/beech–Silver Fir) and orientation (N/S) in providing cooler maximum and warmer minimum temperatures.

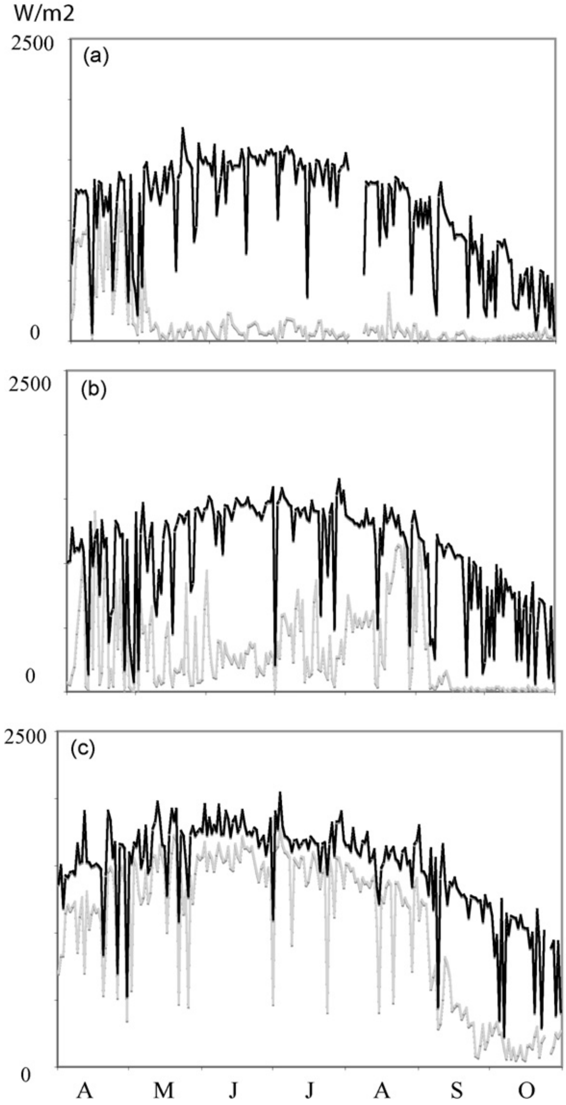

Fig. 4 – Open-field and below-canopy max PAR distribution at Isone (a), Chironico (b) and Visp (c) from April to October 2003.

4. Discussion

In 2003, the temperature differences between open-field and below-canopy were strongest during the very hot 3–13 August period, and they were more pronounced during summer than during the longer period of April to October. The significance levels of differences were highest during June–July–August, particularly for maximum temperature, and lower during April–October. During the 11-day heat wave in August 2003, forest ecosystems offered average maximum temperatures that were cooler by up to nearly 5.5 K. Over the whole summer, the differences could be as high as nearly 5 K and 4 K for the whole season. Over the whole period studied here, from April to October 2003, the correlation tests confirm that for maximum and mean temperature, there is a link between the absolute value of temperature and the degree of impact of the deciduous forest. Particularly during heat wave episodes or, more generally during summer compared to the rest of the season, these forest ecosystems are effective in providing a cool shelter.

The difference between the open-field vs. below-canopy extremes varied considerably from site to site, illustrating the influence of the vegetation type. These differences were more important where beech dominated. Another two forest stations, composed of Silver Fir and Oak, and of Larch and Arolla Pine, also had a significant impact on maximum temperatures. The impact of Spruce and Oak stands was less significant. The sites dominated by Scots Pine and Mugo Pine had the opposite impact on maximum temperatures, which were higher below-canopy than in the open-field. For minimum temperatures, the differences were more important where conifers dominated, while they were least significant for the beech stands.

In some cases, the effect of the canopy on maximum and minimum temperatures was reversed, depending on the species present: those with a strong moderating effect on daytime maximum temperature, beech, beech–Silver Fir, Oak–Silver Fir stands, had little or no impact on minimum temperatures, which as a result of inertia remained relatively lower during the night. In contrast, the species with little or no effect on maximum temperatures, Oak, spruce, pine, had a stronger impact on minimum temperatures, and were consequently warmer below-canopy.

The different impacts of these forest compositions on temperature can be explained in part by differences in canopy closure determining the amount of radiation reaching the ground. The analysis of mean daily PAR shows two main categories of stations: the canopies of most forest types (10 out of 13) stopped 93–97% of the PAR measured open-field between April and October, and 93–99% in summer (Table 2). There was no real difference between stands over the period from April to October but in summer, deciduous and mixed forests, particularly those with beech (except Neunkirch) stopped more radiation than conifer forests. The impact of leaf development in May was visible both in the different amount of PAR reaching the ground in April compared to the three summer months and in the PAR amount below canopy compared with open-field values. The three stations with Pine only blocked approximately half of the radiation.

When only the Beech-dominated sites are examined, it is apparent that slope orientation also has an impact. South- and west-facing sites maintained relatively lower maximum temperatures under the canopy compared to north-oriented sites. The forest thus appeared to offer greater buffering against hot temperatures is situations where the radiation intensity was higher. The relationship between slope orientation and the impact of the forest on minimum temperature was even more obvious, as 5 out of the 7 significant stations were oriented towards the north, and these had minimum temperatures that were relatively warmer.

Additionally, south-oriented slopes had lower differences for minimum temperature. For beech stands only, south-oriented slopes also had greater differences for maximum temperature. We suspect that this is probably due to an inertia effect: on a sunny summer day, the canopy has a stronger influence on maximum temperature on a south-oriented slope than on a north-oriented slope. This lower difference during daytime on north-oriented slopes also explains why, through inertia, the temperature stays comparatively warmer under the canopy during night-time, leading to greater differences between minimum temperature under the canopy and open field.

At the three pine stations, the proportion of radiation blocked by the canopy is clearly lower than for the other stations, corresponding to the degree of canopy closure. The correlation between mean daily temperature difference and PAR difference in- and outside the forest was not or only just significant for these three sites. This means that the impact of the canopy on sun radiation does not explain the impact of the forest on daily mean temperature. This forest impact on temperature is peculiar to the pine forests, particularly the Mugo and Scots Pine ones, where maximum temperature was higher below the canopy. For these two sites, contrary to deciduous forests, the correlation analysis shows that the higher the absolute value of temperature, the higher the positive temperature difference in the forest compared to outside. The structure and height of the Mugo Pine site's canopy may explain why maximum temperatures are higher within the forest. In this natural reserve, there are many dead trees amongst the living ones. The height and diameter of the trees are determined by the high-altitude climate. They grow very close to one another and form an efficient protection against wind and cold, although the very thin canopy lets much of the solar radiation reach the ground. The Scots Pine site, at a lower altitude in the Rhône valley, has unique local climate conditions, being generally dry and very hot during the summer season. Moreover, this stand has also been transformed during our observation period, losing many of the trees (Bigler et al., 2006; Rebetez and Dobbertin, 2004b). Although drought-tolerant deciduous trees are progressively replacing the pine, we suspect that the dominant xerophilic species (Scots pine and Pubescent Oak) affect temperature as less radiating energy is transformed into latent energy. One possibility is that the maximum temperature measured under the canopy is more like that of an open area, but has greater contrast because wind speed is reduced and the heat is not as easily dispersed (Chen et al., 1993), leading to very hot conditions during hot periods.

The impact of pine forests on minimum temperatures is also different to deciduous forests as warmer minimum temperatures were measured under the canopy in Celerina (+5 K) and in Visp (+4 K), both with a strong north-oriented slope, whereas at Nationalpark, on a south-oriented slope, minimum temperatures were lower under the canopy (−0.3 K). High minimum temperatures below-canopy in north-oriented pine forests were probably due to the radiative energy penetrating the forest laterally until sunset because of the unique topography of these sites. However, the relatively small number of sites precludes any firm explanation for the observed patterns.

5. Conclusions

Our results illustrate the moderating effects of different forest ecosystems on local temperatures. They show that the impact of the forest on maximum temperatures is predominantly determined by the forest composition and by the dominant tree species, i.e. factors strongly linked to the degree of canopy closure. The difference appeared to be greater during warmer periods. For minimum temperature (warmer temperatures under canopy), the difference was greater in conifer forests and the determining factor appears to be linked more to slope orientation.

Our results show that forests can offer some relief from the heat. This might become more important in the future as heat waves are expected to become more frequent with climate change. These quantitative results may provide support for afforestation efforts.

The most effective ecosystems in providing a cool shelter during heat waves are beech, beech–Silver Fir and Oak–Silver Fir forests, compared to pure or mixed Norway spruce stands and of course Pine forests which lead to even hotter temperatures under the canopy.

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